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Geomorphology and ecosystems: Challenges and keys for success in bridging disciplines

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Abstract

Geomorphology plays a fundamental role in controlling many ecosystem processes, and in turn, ecosystems can have a profound influence on many geomorphic forms and processes. Over the past few decades, a proliferation of research has developed at the interface of geomorphology and ecosystems ecology. The 2005 Binghamton Symposium brought together some of the leading researchers from both communities to address these critical interfaces between the disciplines. This paper reviews some of the aspects of the disciplines of geomorphology and ecosystems ecology, and the papers presented at the symposium. The papers in this volume illustrate the current status of the disciplines, the difficulties in bridging the disciplines, and the issues that are emerging as research priorities.

Keywords: Geomorphic systems; Ecosystems; Scale; Interdisciplinarity

1. Introduction

Integrating disparate disciplines, with different paradigms, priorities, inherent questions, research methods, approaches, and metrics of success is a fundamental challenge in environmental science. This is particularly true in bridging the disciplines of geomorphology and ecosystems ecology, despite the fundamental role geomorphology plays in ecosystem processes and the apparent similarities in the two disciplines. Many geomorphic processes occur in parallel with ecosystem processes at similar spatial and temporal scales, thus making the two mutually dependent. Predicting future states of the ecosystems on Earth, and developing effective management and restoration practices, necessitates developing a coupled understanding of how these two aspects of the environment influence each other, and how the processes feedback into each other.

The 2005 Binghamton Symposium, held in Buffalo, New York, US, focused on the topic of Geomorphology and Ecosystems, and the papers in this volume were presented and discussed at the symposium. The goal of the symposium was to review, synthesize and discuss the conceptual paradigms, field evidence and simulation models at the intersection between geomorphology and ecosystems ecology, and to identify the critical questions that can motivate future research, and will enhance the

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effectiveness of the future management and restoration of ecosystems.

In this paper, we briefly describe the scientific background and developments leading to the coupling of research in geomorphology and ecosystem ecology. We then examine the significant questions at the interface of geomorphology and ecosystems that are critical to the research and management communities, as well as the techniques and conceptual approaches that are common within each field. Throughout this paper we highlight the issues and insights that were gained as a part of the papers and discussions during the Symposium, and we point the reader to the papers in this volume that provide insight into these discussions.

2. Need for integration of geomorphology and ecosystem ecology

2.1. Global environmental change

Humans have dramatically altered the ecosystems on Earth, through, inter alia, agricultural development, introduction of exotic species and changes to biogeochemical cycles (see reviews by Vitousek et al., 1997; Meybeck and Vorosmarty, 2004). As a consequence, geomorphic processes, such as accelerated soil erosion and fluvial activity, are responsible for some of the most critical environmental issues — issues like the loss of productive top soil, degrading water quality and the loss of navigable waters, to name but a few. Whereas advances have been made in understanding many of the processes leading to changes in ecosystems, recent scientific advances have shown the joint nature of biotic and abiotic processes driving many ecosystem changes and the nature of feedback processes between physical and ecological systems (e.g., Zeng et al., 1999). Detail on the coupling effects between these two systems, however, is poorly understood (e.g., Scheffer et al., 2001). Thus, with increasing pressures on the environment, a strong trend exists to manage environmental ecosystems. This requires a holistic, interdisciplinary approach that simultaneously considers the physical, chemical and biological components of environmental systems (Thoms and Parsons, 2002).

Many disciplines are often bought together to solve environmental problems. The integration of disciplines, however, is fraught with challenges that can potentially reduce the effectiveness of interdisciplinary approaches to environmental problems. Pickett et al. (1994) identify three consequences of disciplinary progress:

(a) gaps in understanding appear at the interface between disciplines;
(b) disciplines focus on specific scales or levels of organization; and,
(c) as sub disciplines become rich in detail they develop view points, assumptions, definitions, lexicons and methods.

These consequences often impede the integration of disciplines into a single applied understanding of environmental systems because attempts to produce an interdisciplinary outcome tend to remain dominated by the paradigms familiar to component disciplines. Successful interdisciplinary science requires the ’explicit joining of two or more areas of understanding into a single conceptual–empirical structure’ (Pickett et al., 1994). Integration of disciplines can be additive or extractive. In additive integration, two areas of understanding are combined more or less intact into a new composite understanding. In extractive integration, two or more areas of understanding may provide components that are combined to yield a new understanding. Both processes are relevant in environmental science, depending on the nature of the problem at hand and the state of knowledge in component disciplines.

2.2. Emerging issues in environmental sciences

Many emerging environmental issues are difficult to comprehend because they fall at the interface of geomorphology and ecology, and thus inherently draw upon disparate scientific backgrounds, necessitating inter-disciplinary approaches to problem identification, research, and recommendations of solutions. This problem is not unique, however: examining the US National Research Council’s suggested ‘Grand Challenges in the Environment’ shows that the most important questions scientists now face are those that necessitate explicitly inter-disciplinary research (National Research Council, 2003). The identified priority areas are:

1. biogeochemical cycles,
2. biological diversity and ecosystem functioning,
3. climate variability,
4. hydrologic forecasting,
5. infectious diseases in the environment,
6. institutions and resource use,
7. land-use dynamics, and
8. reinventing the use of materials.

Thus, within environmental science, disciplinary boundaries are beginning to be blurred to tackle critical emerging issues. Combining geomorphology and ecosystem ecology then is not unique, but is representative of the new paradigm in environmental science.

Central to addressing many of these emerging issues, particularly that of large scale environmental restoration (e.g., controlled floods on Grand Canyon, Everglades restoration; Borg et al., in press; Jackson et al., in press), is the understanding of coupling biotic and abiotic processes. Recent studies have begun to emphasize the potential role of the physical landscape, or geomorphology, in ecological processes (e.g, Claussen et al., 1999; Alexander et al., 2000; Hamilton et al., in press). Whereas links between geomorphology and organism populations and communities are relatively well-studied, we have only recently begun to explore how changes in physical heterogeneity of habitat influence ecosystem-level processes, such as primary productivity, the cycling of nutrients (Cardinale et al., 2002; Chadwick et al., in press; Fisher et al., in press; McKnight et al., in press), or ecological processes at the scale of entire food webs (Post et al., in press). Thus, it is imperative at this point in time to continue traditional fruitful research in the area of geomorphology and community ecology, also to advance beyond this into research at the interface of geomorphology and entire ecosystem ecology. Moving into this potentially highly lucrative research arena is likely to reveal fundamentally new aspects related to feedbacks and thresholds between geomorphology and ecosystems (Neave and Rayburg, in press). Exploring these interface research areas is likely to trigger fundamentally new research for the next decade.

3. Development, challenges, and prospects for integration

3.1. Parallel disciplinary trajectories of geomorphology and ecosystems ecology

Understanding the different paradigms of geomorphology and ecosystem ecology is important for the successful integration of these two disciplines. Both have progressed and evolved over the past century, and understanding this parallel development helps understand how to bridge geomorphology and ecology for future research.

3.2. Geomorphology

Geomorphology is primarily concerned with the formation of the surface of Earth and how change occurs over time and space. Studies of hill slope erosion, chemical denudation, aeolian sediment transport, coastal and fluvial processes have received much attention. Geomorphology, as a science, was dominated by physical geographers for much of the early 20th century, with the dominant paradigm being the description of landscape forms. Geomorphology underwent substantial growth toward a more quantitative discipline, in the 1950s, in which landscape forms were quantified rather than just being described. This period was dominated by extensive field campaigns by geographers and geologists where insights into landscape forms were developed via intense observations (e.g., Leopold and Maddock, 1953; Wolman and Leopold, 1957). In particular, the accumulation of quantitative data from varying regions of the world allowed geomorphologists to synthesize landforms into classifications, note broad-scale systematic variability in landscape forms, and to speculate on the probable mechanistic drivers of these patterns.

In the following decades, the discipline of engineering provided tools and methods for quantifying the dynamic processes associated with geomorphic forms, i.e., how landscape changes through time, and eventually, models for predicting these changes. Engineering also brought with it a paradigm of experimental modeling, particularly physical scale-modeling experiments (e.g., flumes, soil erosion). Thus, geomorphology incorporated a decidedly robust modeling perspective during the latter decades of the 20th century, leading to the development of a host numerical models of specific landscape processes.

More recently, geomorphology has taken great strides in expanding the spatial scale of research via remote sensing (RS) and Geographic Information Systems (GIS), and integrating insights from other disciplines to more fully understand external drivers of landscape forms and processes (e.g., climate-landscape coupling (Zeng et al., 1999)). The process-based understanding and the numerical models developed previously are now being applied to large spatial scales that allow geomorphologists to explore landscape processes at the scale of entire continents and even other planets (Claussen et al., 1999). Further, integrating insights from other disciplines (e.g. atmospheric sciences) has promoted an expansion of geomorphology into exploring complexities and feedbacks between systems (e.g., climate driving landscape changes, landscape changes in turn affecting subsequent climate patterns (Brovkin et al., 1998)).

Thus, the historical roots of geomorphology provide a rich history of exploring spatial variability in landforms, the timescales over which these landforms adjust, and through engineering, quantifying the actual physical processes that lead to these landforms. Further, geomorphology, particularly over the past two decades, has proven itself to be an extremely nimble and integrative discipline in terms of informing and being informed by insights from other disciplines (Rhoads and Thorn, 1996).

3.3. Ecology and ecosystems research

Ecology has traditionally been concerned with interactions between organisms and their environment. It was dominated in the early and mid 20th century by descriptive, field-based studies, much like geomorphology. In subsequent decades, ecology progressed toward a more theory-based community perspective, seeking to understand and synthesize spatial and temporal patterns in community structures. The 1970s and 1980s saw an increasing interest in the processes of ecology, thus the incorporation of experimental studies: the mesocosms for ecologists were similar subsystems as flumes for geomorphologists. Ecology has more recently incorporated a greater role of theoretical and modeling-based studies, with particular interest in complex interactions (e.g., Scheffer et al., 2001). Like geomorphology, ecology has also seen a drastic increase in the spatial and temporal scales of its study: whereas RS and GIS promoted landscape evolution studies in geomorphology, the same technology promoted the parallel development of landscape ecology. In all, ecology has a rich history of spatial and temporal studies, substantial empirical databases, process-based models at the landscape scale, and a tendency to integrate with other disciplines.

Within the discipline of ecology, a division of varying intensity occurred between those focusing primarily on organismal dynamics (the population–community approach) versus those interested in physical, chemical, and biological dynamics of whole ecosystems (the ecosystem or 'process-function' approach, sensu O'Niell et al. (1986). In the former case, the environment is a back-drop or external driver in the study of biotic phenomena, such as population growth, competition, predation, and life history dynamics; in the latter, the consequences of interactions between organisms and the environment are the featured attraction. Ecosystem ecology emphasizes the functional roles of organisms (what they do) rather than the specific identity (which species are present), and relies heavily on measures that integrate physical, chemical and biological processes and components. These measures generally fall into the broad categories of energy flow (e.g., primary production, decomposition) and nutrient cycling. The gulf between the two sub disciplines has been substantial at times, but a rich portfolio of examples now illustrates the point that who is present can affect whole-ecosystem processes. Indeed, understanding the strength and nature of the effects of species composition on ecosystem function is currently a topic of intense study and debate amongst ecologists (e.g., see Jones and Lawton, 1994; Grime, 1997; Olden et al., 2004).

3.4. Integrating geomorphology and ecology

Based on these parallel histories, one would expect that these two disciplines would easily merge into well-meshed integrative studies, co-informing each other and developing truly integrative and over-arching theories. This has not been the case. Instead, the two disciplines have tended to perform research in relative isolation, selectively picking and choosing snippets of information and theory from the other discipline when needed.

Much of the traditional work of geomorphologists in exploring ecological processes has been limited to investigating how geomorphic forms or processes affect specific species, or groups of species (e.g., fish, trees), or vice-versa. Geomorphologists, however, have been somewhat absent in contributing to an understanding of ecosystem ecology. It is likely that landscape features have profound influence on whole ecosystem-level processes that have, to date, been largely missed by geomorphologists because they were only considering ecological processes at the community or organism level, which were not necessarily impacted by geomorphology.

The problem from the other side of the aisle is possibly just as severe. The bulk of ecological studies have dominantly treated geomorphic forms as static. That is, the dominant ecological research paradigm considers the physical landscape a static template upon which ecological processes occur. In contrast, the discipline of geomorphology is primarily focused on the dynamic nature of landscapes and quantifying the contributing processes and the timescales over which these processes occur. Many geomorphic changes occur on spatial and temporal scales comparable or even parallel with ecological changes, thus making biotic and abiotic processes variable rather than static parameters within ecosystem studies. Thus, in trying to link the disciplines of geomorphology and ecosystem ecology, a fundamental mis-match occurs between how ecologists and geomorphologists consider the physical landscape.

Attempts have been made to integrate the disciplines of geomorphology and ecology. Recently, Thoms and Parsons (2002) proposed a framework for the interdisciplinary study of river ecosystems. Ecogeomorphology integrates ecology into hydrology and geomorphology, geomorphology and hydrology into ecology and hydrology into ecology and geomorphology. This framework has been successfully employed to the study of environmental allocations of water for dryland river systems. Nonetheless, this integration is still in its infancy. Thus, bridging the gaps in research and applications between the disciplines of geomorphology and ecosystems ecology was the goal of the 2005 Binghamton Symposium.

4. Lessons from the Binghamton Symposium: cross-fertilization, emerging issues, and limitations

4.1. What can geomorphologists and ecologists learn from each other?

Taking a geomorphic perspective of ecosystems ecology provides a 'place-based' and 'time-based' view of ecological processes, and also can provide some mechanistic and quantitative tools (i.e., process-based models) for predicting how landscapes will change through time and space. Thus, if an ecological process is a function of a particular landscape feature, a geomorphic perspective can provide information on how that ecological process should systematically vary through space and time, and potentially qualitatively or quantitatively predict those variations using available dynamic process-based geomorphic models.

A good example of this type of cross-fertilization in river research is how fundamental geomorphic understanding of hydraulic geometry in channel networks allowed the creation of the River Continuum Concept in stream ecology (Leopold and Maddock, 1953; Vannote et al., 1980). Another example is Chadwick et al.'s (in press) study of the historic spatial distribution of vegetation and soil nutrients in Hawaii, as their soils research provided a longer-term and larger spatial understanding of currently observed soil biogeochemistry. Gurnell et al. (in press) provide an example of how relatively simple understanding and quantification of geomorphic processes (sediment movement) can improve our understanding of the movement of vegetation fragments and propagules through channel networks. At a much larger scale, Hamilton et al. (in press) use floodplain geomorphology and hydrology to understand physical controls on floodplain biodiversity. Across a wide range of spatial and temporal scales, McTainsh and Strong (in press) show how aeolian erosion helps explain nutrient fertilization of distant ecosystems, and thus, that widely spaced ecosystems can be strongly linked by geomorphic processes.

On the other side, an ecosystem ecology perspective helps provide geomorphologists a more holistic view of the nested ecological processes and the process dynamics (e.g. ecosystems, habitat, population dynamics, food webs) over appropriate spatial and temporal scales. Linking vegetation and geomorphic forms continues to be a core component of understanding these coupled systems (e.g., Hamilton et al., in press), as this linkage helps to understand hillslope processes in steep terrains (Geertsema and Pojar, in press), historic erosion patterns associated with human modification (Bork et al., 2005; Chadwick et al., in press), as well as critical issues of nonlinear landscape responses (Neave and Rayburg, in press). Two papers presented at the symposium, however, provide a particularly intriguing set of questions and observations: Fisher et al. (in press) pose the question, based on arid stream research, of whether biogeochemical processes could possibly affect geomorphic forms, and Watters and Stanley (in press) provide some preliminary observations of peatland channels where such linkages may be occurring. Equally intriguing is the study of dry Antarctic channels by McKnight et al. (in press) that shows the preservation of microbial mats in a cryptobiotic state in a dry channel for over two decades. In these unusual or even extreme settings, questions of process interactions may become more clear.

4.2. Questions of scale

An important issue that arises frequently in coupled research of geomorphology and ecosystems ecology is that of scale; problems associated with selecting an appropriate scale for research and analysis emerged frequently during the symposium. Scale is a critical issue in designing a study and collecting data, but also in less recognized issues such as model development and selection and data availability and quality (Parsons and Thoms, in press).

Post et al. (in press) examined how scale is interpreted in geomorphology and ecology, particularly as it relates to entire food webs in ecology. Parsons and Thoms (in press) address the issue of scale through an explicit analysis of hierarchical processes in stream ecosystems. Hierarchy also plays an important role in the conceptual model developed by Dollar et al. (in press). Discussion during the symposium indicated that the issue of hierarchical processes and theory was a conceptual area common in geomorphology and ecosystems ecology, and, thus, is one that merits further research on both sides as an interface topic. Issues of how processes scale across space were addressed by McTainsh and Strong (in press) in examining aeolian erosion, and Bork et al., (2005) examine anthropogenic soil erosion across a wide variety of temporal scales.

Based on the discussions and the papers here, we suggest that exploring the coupling of ecosystem and

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geomorphic processes across a wide variety of scales is a potentially lucrative area of research. Some scales of interaction are well researched, e.g., the effect of vegetation on erosion or river migration over annual to decadal timescales. Others are less well understood, however, and could pose conceptual and logistical challenges. These scales are likely to be the extremely small scales (sub-meter) and extremely large scales (continental) and how, or even if geomorphic and ecosystem processes are linked at these scales, and where there may be potential causality shifts. We suggest, however, that a few of the papers point in the direction of how to approach these questions, particularly McTainsh and Strong's (in press) as an example of studying a particularly process across a widely disparate spatial and temporal scale.

4.3. Limitations

As part of the symposium and the papers presented, we identified numerous limitations to bridging geomorphology and ecosystems ecology, and, thus, important conceptual issues needing to be addressed in research. Foremost of these was that core, guiding research questions in the two disciplines are often divergent, and, thus, can take the two fields in widely disparate directions. Key questions in a discipline shape the dominant paradigms of research within that discipline, and thus research priorities for long periods of time. When questions or paradigms converge, great insights in both disciplines can emerge (e.g., River Continuum Concept, Vannote et al., 1980). At present, it seems that one of more lucrative areas of coupled research is bridging landscape ecology and landscape evolution, as both areas of research are priorities in the respective communities. The second commonality in research in both disciplines is ecological restoration. These are addressed below.

Along with key questions, a limiting factor in collaborative research is identifying fundamentally different approaches used by different disciplines. We expect, based on the histories of geomorphology and ecology as articulated above, that the methods and approaches of the two disciplines will actually be very comparable and compatible, and, thus, it is equally important to make geomorphologists and ecologists fully aware of these similarities (e.g., spatial analysis and modeling with RS and GIS in landscape evolution and landscape ecology, experimental field manipulations for disturbance recovery studies). Indeed, we suggest that the increasingly focused use of GIS and RS has facilitated enhanced collaboration (e.g., Hamilton et al., in press), although future research in this arena will necessitate increased consideration of timescale and forecasting and modeling by ecologists to fully inform geomorphic process modeling.

As part of this increased collaboration, and particularly forecasting and modeling, we must increasingly identify what spatial and temporal data are actually currently available within geomorphology and ecosystems ecology. This will first make the disparate disciplines aware of datasets, or the kinds of data, used by other disciplines. Also we must identify substantial missing components of data and problems with data availability that would enhance the understanding of the dynamic in landscape ecosystem processes and promote or facilitate inter-disciplinary research in the future.

As data continue to become available at increasingly larger scales, an increased need will occur for theoretical and applied modeling, particularly for education (Carpenter, 2003). Many models are discipline specific, however, and scientists outside of a particular discipline may not be aware of the existence of other models or their relative ease or difficulty of use. Thus, making scientists aware of the types of models available, as well as the specific models that are frequently used by the various disciplines, is a key aspect bridging geomorphology and ecosystems ecology. Further, it is necessary to exchange ideas of how to adapt, modify and possibly integrate the models from other disciplines to create true landscape ecosystem models.

The final limitations to future interactions are the pitfalls associated with the increased reliance on graphical tools (maps, aerial photographs, and digital imagery) in the interaction between geomorphologists and ecosystems ecologists. GIS have emerged as a powerful tool in both disciplines, with modern information technology (e.g., GIS applications through the Internet). GIS applications can be used to answer meaningful questions in formats usable for decision-makers. To achieve this potential, however, each application of a GIS-based model has to be evaluated in terms of its ability to provide the user with useful visual information and analysis tools while fulfilling the data quality standards and preprocessing requirements of the model (Renschler, 2003). Poor quality of spatio-temporal data, data processing induced errors in data conversion, and error levels introduced by model assumptions and methods need to be evaluated carefully in terms of the potential effect on results and the decision-making process. GIS-based models can also over-extend the true understanding of the underlying processes, possibly providing decision-makers with a false sense of predictability. Geomorphologists and ecologists play therefore unique roles in enhancing the communication among scientists, natural resource managers, decision-and policy-makers and other stakeholders providing integrated concepts, models, and other assessment tools through research in their disciplines (see also Renschler and Harbor, 2002). Techniques, such as statistical modeling and accuracy visualization, provide ways to show users the accuracy of data and choices of the model affect results and, thus, decisions. The accuracy of coupled eco-geomorphic models remains a critical need in research.

4.4. Emerging issues and future of research

The greatest emerging issues that were identified at the symposium were (1) coupled landscape ecology and landscape evolution modeling, and (2) ecological restoration. These issues are critical research frontiers because they necessitate a thorough understanding geomorphology and ecosystems ecology. For landscape evolution and ecology, the challenge is to bridge both disciplines, but to do so in a way that allows extrapolation and prediction through space and time. Extending and predicting ecosystem processes through time, and predicting how these feedbacks to geomorphic changes will be the greatest challenges for bridging disciplines.

The role of prediction is also critical in ecological restoration. The papers addressing ecological management and restoration ranged from soil and organic matter erosion (Ritchie et al., in press), to stream ecological restoration (Borg et al., in press) to beach renourishment (Jackson et al., in press), and illustrated the dynamic tension between the realities of scientific understanding and the needs of the management community. Restoration is a particularly important issue for the research community because it necessitates understanding the science of both disciplines, and also necessitates a level of accuracy and precision in prediction and modeling of the coupled systems that is often not present. Geomorphologists and ecosystems ecologists have developed excellent abilities to qualitatively predict responses to management actions via conceptual models (e.g., Dollar et al., in press), but extending these to quantitative predictions remains a significant challenge.

Increasing this level of accuracy and precision in prediction over relatively short timescales (e.g., decade) for restoration and management, and then increasing the timescale of coupled predictive modeling (century to millennium), we suggest are the key challenges to the research community. Within this predictive capacity we truly learn the limits of our understanding of these systems, and, thus, these applications of science are likely to guide future research agenda. Such modeling efforts will shed light on processes not fully understood, data limitations in time and space, and most importantly, whether current paradigms of education and training are sufficient for these emerging issues. The papers presented at the Binghamton Symposium illustrate the rich history and current status of research in geomorphology and ecosystems research and point to the way to the emerging paradigms of research in the coming decade.

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